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A Structured Decision Framework for Improving Solar PV Integration and Frequency Stability Using Kepner–Tregoe and Analytical Hierarchy Process: A Case Study of PT OEC

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Abstract:
The increasing penetration of solar photovoltaic (PV) generation in industrial power systems offers significant opportunities for fuel reduction and sustainability improvements. However, high PV penetration also introduces operational challenges related to power variability and grid frequency stability, particularly in systems with limited inertia and spinning reserve. This study proposes a structured managerial decision framework to address solar PV integration challenges at PT OEC by combining Kepner–Tregoe (KT) problem analysis and the Analytic Hierarchy Process (AHP). Solar PV performance and grid frequency behavior were first analyzed to identify whether observed disturbances were caused by technical failures or structural system limitations. KT analysis was then applied to validate the root causes of frequency instability events. Based on the identified causes, four alternative solutions were evaluated using AHP across multiple criteria, including frequency stability improvement, PV energy yield impact, investment cost, implementation complexity, and operational maintainability. The results indicate that a Battery Energy Storage System (BESS) is the most preferred strategic solution, followed by gas turbine spinning reserve optimization and PV–GT coordination procedures. Sensitivity analysis confirms that while BESS dominates under reliability-focused priorities, operational measures remain relevant under cost- and time-constrained scenarios. The study demonstrates that combining KT and AHP provides a robust decision-making framework for balancing reliability, cost, and long-term value in solar PV integration.
Keywords: *Keywords: Solar PV integration; Frequency stability; Kepner–Tregoe; Analytic Hierarchy Process; Decision-making; Case study*

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INTRODUCTION

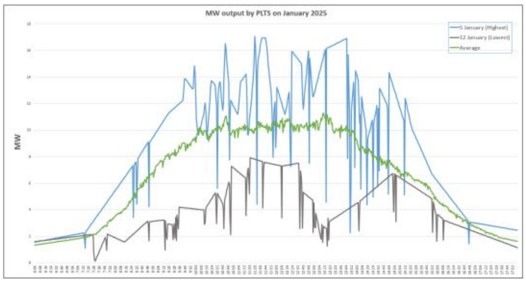
The deployment of solar photovoltaic (PV) generation has accelerated across industrial power systems as organizations pursue fuel efficiency, emission reductions, and sustainability targets. In isolated or semi-isolated industrial grids, solar PV offers substantial economic and environmental benefits by displacing thermal generation. However, the inherent variability of solar PV output introduces operational challenges that extend beyond conventional technical performance considerations (Alshahrani et al., 2019; Bistline, 2017; Hidayatullah, 2019; Shafiullah et al., 2022).

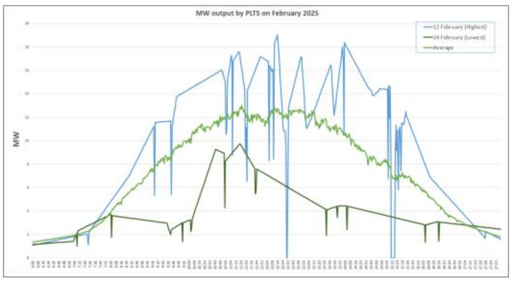
At PT OEC, integrating a 25 MWp solar PV portfolio into the internal power system has coincided with two interrelated issues. First, the realized energy output of the PV plants has remained at the lower bound of regional benchmarks, raising concerns about unrealized energy value (Alghanem & Buckley, 2024; Breyer et al., 2023; Ferroni & Hopkirk, 2016; Huxley et al., 2022). Second, several grid frequency disturbance events—including Under-Frequency Load Shedding (UFLS) activation—have occurred during periods of constrained system operation, despite the absence of generator trips. These events suggest that the challenges involve not only equipment performance but also system-level balancing capability and operational flexibility.

Existing studies on PV integration often focus on technical mitigation measures or single-criterion optimization, such as minimizing cost or improving power quality (NREL, 2020; Ulbig, 2014; IEA, 2021; ENTSO-E, 2018; Ela, 2011; Wärtsilä, 2020). However, managerial decision-making in industrial power systems requires balancing multiple, often competing, objectives, including reliability, economic impact, implementation feasibility, and long-term strategic value (Das et al., 2018; Jones, 2017; Parker et al., 2019; Sim, 2023). Although methods such as Kepner–Tregoe (KT) and Analytic Hierarchy Process (AHP) have been widely used in decision-making contexts (Kepner & Tregoe, 1981; Saaty, 1980), their combined application in addressing solar PV integration challenges—particularly in industrial power systems with frequency stability constraints—remains underexplored. This gap is especially relevant in systems like PT OEC's, where operational, economic, and strategic factors must be balanced under technical and resource constraints (Arifin et al., 2024; Hutahaean, 2024; Utomo et al., 2025; Wibowo et al., 2024).

This study addresses this gap by proposing a structured decision framework that integrates Kepner–Tregoe problem analysis and the Analytic Hierarchy Process to systematically diagnose root causes and prioritize solutions for solar PV integration under frequency stability constraints. The framework enables multi-criteria evaluation that balances reliability, economic impact, implementation feasibility, and long-term strategic value—a perspective often missing in purely technical studies. The objective is to identify and prioritize feasible solutions that enhance grid reliability while preserving the economic and sustainability benefits of solar PV generation, using PT OEC as a representative industrial case study.

The findings offer both practical and theoretical benefits. Practically, the proposed framework provides PT OEC and similar industrial operators with a clear, phased implementation roadmap to enhance frequency stability while optimizing PV energy yield. Theoretically, this research contributes to the growing body of knowledge on integrated decision-support systems for renewable energy integration, offering a replicable methodology that combines technical analysis with managerial decision-making.





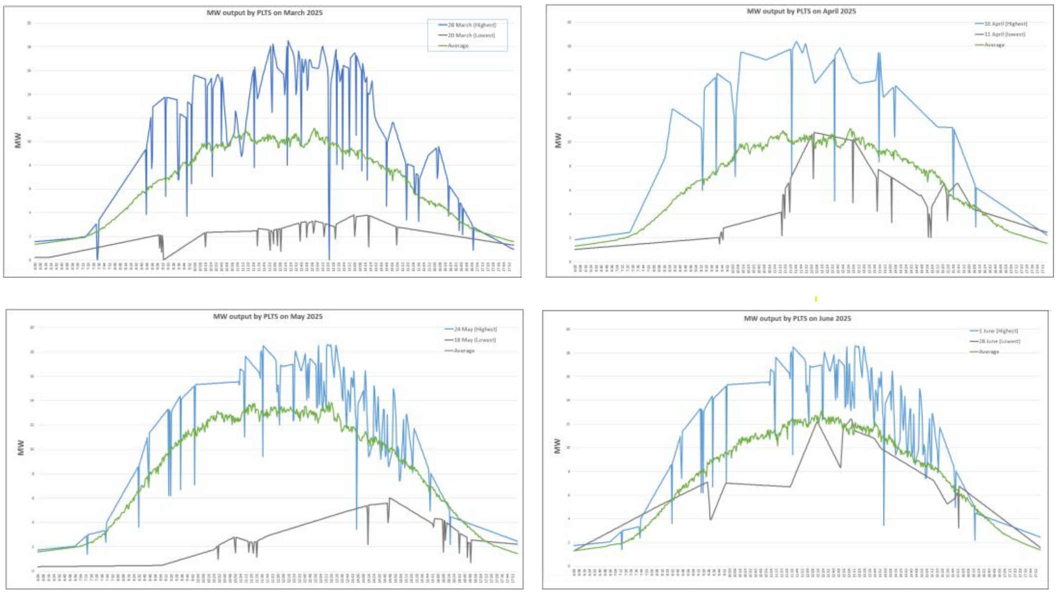


Figure 1. Typical daily power output profile of Solar PV between January-June 2025
Source: PT OEC operational data, 2025

RESEARCH METHODOLOGY

This research employed a mixed-methods design to address solar PV underperformance and grid frequency stability challenges at PT OEC by integrating qualitative managerial insights with quantitative operational data. The methodology combined solar PV performance evaluation and grid frequency analysis with structured problem diagnosis using Kepner–Tregoe Problem Analysis to validate root causes, followed by solution prioritization using the Analytic Hierarchy Process (AHP). Operational data from PV generation, grid frequency records, and disturbance events were analyzed alongside expert judgment to assess alternative solutions based on multiple criteria, including reliability impact, economic considerations, and implementation feasibility. Sensitivity analysis was further applied to evaluate the robustness of the decision results under varying managerial priorities, ensuring that the proposed recommendations were both analytically sound and practically applicable.

From a research purpose perspective, the study was exploratory-evaluative in nature. The exploratory dimension identified root causes and contextual factors influencing PV performance and grid behavior through Kepner–Tregoe (KT) analysis, while the evaluative dimension applied AHP to prioritize improvement strategies across the specified criteria. This sequential, integrated approach ensured evidence-based problem diagnosis and systematic assessment of solutions before formulating recommendations, aligning the design with the study's objectives.

Tabel 1. Summary of Research Design Characteristics

Aspect	Description
Approach	Mixed-method (Qualitative + Quantitative)
Purpose	Exploratory + Evaluative
Philosophy	Positivism (structured analysis) + Pragmatism (practical solution focus)

Orientation	Explanatory (root cause), Evaluative (solution assessment) and Preventive/Forward-Looking.
Frameworks Used	KT Situation Analysis, Problem Analysis, Potential Problem Analysis (PPA) and Analytic Hierarchy Process (AHP)

Source: Researcher's analysis, 2025

The flowchart illustrated the sequential steps undertaken to address the identified business issues related to solar PV integration and grid frequency stability at PT OEC. Unlike the conceptual framework presented in Chapter II, which explained the theoretical relationships among key concepts, this flowchart focused on the procedural execution of the research, outlining how the study progressed from problem identification to conclusions and managerial recommendations.

This study relied on primary data collection to capture organization-specific operational insights related to solar PV performance and grid stability at PT OEC. Qualitative data were obtained through semi-structured interviews with key stakeholders, including engineers, operators, and managers directly involved in PV plant operation, maintenance, and decision-making. The interview approach allowed flexibility to explore emerging issues while maintaining consistency across respondents, focusing on operational routines, observed performance deviations, previous corrective actions, and the feasibility of potential improvement measures.

In parallel, quantitative data were collected from internal performance reports and operational logs, including energy yield, system efficiency, downtime incidents, and grid-related events.

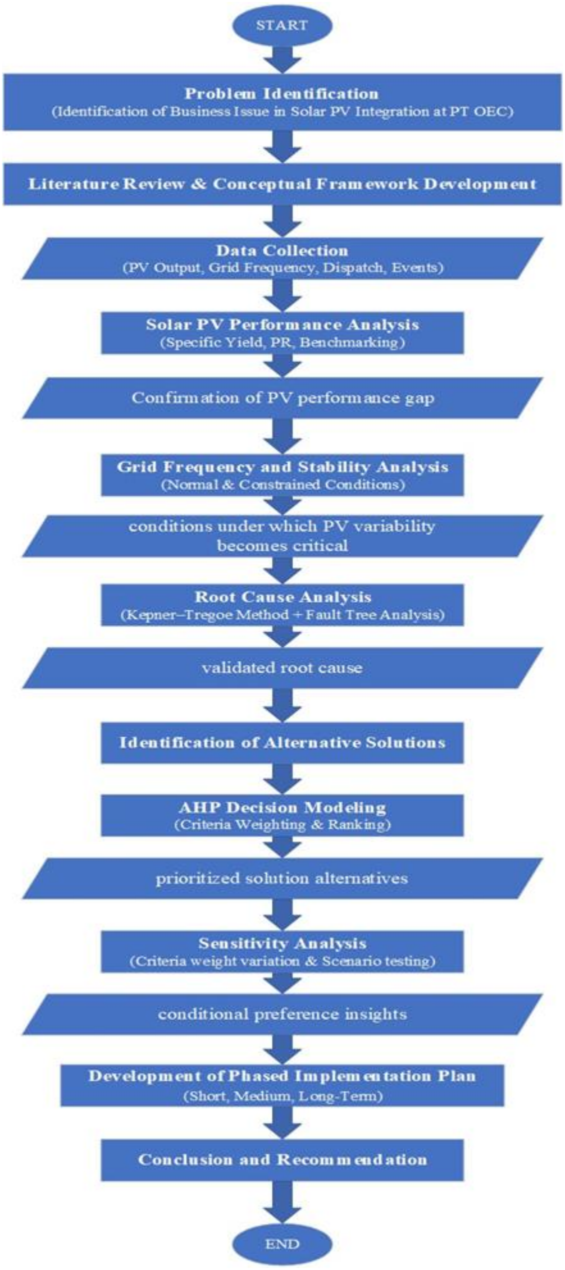


Figure 2. Research Methodology Flowchart
Source: Developed by the researcher, 2025

Table 2. Summary of the key aspects of the data collection plan

Data Type	Method	Source/ Respondents	Purpose
Qualitative Data	Semi-structured Interviews	Engineers, Operators, Managers	Identify root causes and solution ideas
Quantitative Data	Document Analysis	Internal reports and operational logs	Validate findings, support AHP inputs

Source: Developed by the researcher, 2025

This study applied a structured data analysis approach consistent with its mixed-methods research design to examine solar PV performance and grid stability at PT OEC. Qualitative data obtained from semi-structured interviews were analyzed using thematic coding to identify recurring operational issues and contextual factors influencing PV performance. The extracted themes were subsequently structured using the Kepner–Tregoe (KT) Problem Analysis framework to systematically characterize the problem, distinguish relevant changes, and validate the root causes of observed performance degradation and frequency disturbances at the grid interface.

Quantitative analysis was conducted using descriptive statistics and gap analysis based on operational logs, PV performance reports, and grid frequency records. Key performance indicators—including energy yield, capacity factor, and frequency deviation—were evaluated to identify trends, anomalies, and deviations from industry benchmarks. The validated findings from the qualitative and quantitative analyses were then integrated into a multi-criteria decision-making process using the Analytic Hierarchy Process (AHP) to prioritize improvement alternatives based on reliability impact, economic considerations, and implementation feasibility. This triangulated approach enhanced analytical rigor and supported robust, actionable recommendations for both plant-level optimization and system-level reliability improvement.

Table 3. Summary of Data Analysis Methods

Data Type	Source	Analysis Method	Purpose / Output	Relevance to Research Objectives
Qualitative – Narrative Insights	Semi-structured interviews with operational team, engineers, and managers	Thematic Coding → Identify recurring operational issues and perceptions; Kepner–Tregoe (KT) Problem Analysis → Isolate root causes	Categorized themes, root cause map (what, where, when, extent)	Explains *why* PLTS underperforms and identifies operational factors affecting grid stability
Quantitative – Operational Performance Data	Daily operational logs, energy yield reports, downtime logs	Descriptive Statistics → Summarize kWh output, capacity factor, downtime frequency; Trend Analysis → Detect anomalies	Performance trends, baseline operational profile	Measures *how far* actual performance deviates from design capacity; supports correlation with grid stability events
Quantitative – Grid Stability Metrics	Grid interface monitoring data (frequency deviation, voltage fluctuation, disturbance logs)	Statistical Comparison & Gap Analysis → Compare metrics vs. grid code limits and benchmarks	Stability impact score, compliance gap map	Quantifies effect of PLTS operation on grid reliability
Quantitative – Benchmarking	UTHM 6.9 MWp Malaysia (journal), regional PV studies	Comparative Performance Benchmarking (PR, yield, CF, climate similarity)	Establish realistic performance targets & identify underperformance	Supports PLTS performance gap analysis

Data Type	Source	Analysis Method	Purpose / Output	Relevance to Research Objectives
Mixed – Decision-Making Data	Expert judgment, operational & stability records	Analytic Hierarchy Process (AHP) → Criteria weighting (cost, reliability, feasibility, grid impact), alternative ranking	Ranked improvement strategy list with consistency check	Identifies the most feasible and impactful optimization strategy, balancing plant performance and grid stability
Integrated Findings	Outputs from qualitative & quantitative analyses	Triangulation → Cross-validation of findings across methods	Final integrated diagnosis & recommendations	Ensures solutions are grounded in evidence, operationally realistic, and supportive of system-wide stability

Source: Developed by the researcher, 2025

RESULTS AND DISCUSSION

This section establishes the analytical context for evaluating solar PV performance and grid frequency behavior within PT OEC's internal power system. The integration of a 25 MWp solar PV portfolio introduces both value optimization opportunities and operational reliability challenges arising from the interaction between variable renewable generation and a gas turbine–dominated system with limited flexibility. While PV variability can be managed under adequate spinning reserve and system inertia, constrained operating conditions—such as reduced reserve, base loaded gas turbines, and unit outages—may increase frequency sensitivity and operational risk. Accordingly, the analysis is structured to first assess whether a measurable PV performance gap exists relative to comparable tropical systems, and subsequently examine how PV variability interacts with system conditions to influence frequency stability, providing a coherent foundation for root cause analysis and solution prioritization in the following sections.

Solar Performance Analysis

The operational performance of PT OEC's 25 MWp solar PV portfolio was evaluated using six months of high-resolution operational data from January to June 2025. Prior to analysis, the dataset was reviewed and cleaned to ensure reliability, including the treatment of several days affected by communication failures that resulted in near-zero recorded output despite normal irradiance conditions. After data cleaning and imputation, consistent daily and monthly performance metrics were established as the basis for evaluation.

The results show a clear seasonal performance pattern, with higher energy yield observed from April to June, corresponding to relatively drier conditions and more stable solar irradiance. The average specific yield across the study period ranges from approximately 3.1 to 3.9 kWh/kWp/day, while peak power levels remain within the expected range of 18–21 MW, considering system design and temperature derating. These findings indicate that the PV plants are operating in a stable and technically acceptable manner, although overall performance remains at the lower bound of typical tropical benchmarks.

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Table 4. Monthly PV Performance (January–June 2025)

Month	Total Energy (MWh)	Avg. Daily Energy (MWh/day)	Approx. Specific Yield* (kWh/kWp/day)	Peak Power (MW)
January	2,413.69	77.86	≈3.11	18.92
February	2,471.68	88.27	≈3.53	20.76
March	2,364.25	76.27	≈3.05	20.12
April	2,797.44	93.25	≈3.73	20.11
May	3,022.07	97.49	≈3.90	19.38
June	2,938.04	97.93	≈3.92	18.58

Source: PT OEC operational data, 2025

Frequency Stability Analysis

Frequency stability is a critical indicator of operational reliability in PT OEC's internal power system, particularly in the context of increasing solar PV penetration and heavy reliance on gas turbine units for balancing. Analysis of one-minute frequency data shows that under normal operating conditions the system frequency remains stable, with mean values close to 60 Hz and typical deviations within ±0.05–0.10 Hz, which are well inside the ±0.2 Hz operating limits specified in the Indonesian Grid Code. These results indicate that, during periods with adequate spinning reserve and system inertia, solar PV variability does not materially compromise frequency stability.

However, two major disturbance events on 22 May and 1 June 2025 reveal a markedly different behavior under constrained operating conditions. Both events resulted in under-frequency load shedding (UFLS) activation despite the absence of generator trips, indicating a system-level balancing issue rather than equipment failure. Operational records show that during these events the system was operating with significantly reduced flexibility: one large NDC unit was offline, gas turbines were near baseload with limited ramping capability, and available spinning reserve dropped to only 0–5 MW, far below the normal requirement. At the same time, rapid PV output reductions of approximately 10–17 MW occurred due to fast-moving cloud cover. The resulting sudden increase in net load led to steep frequency declines, with minimum frequency reaching approximately 59.69 Hz and high rates of change of frequency, ultimately triggering UFLS protection.

PV-Frequency Interaction

These disturbance events did not occur in previous years because system conditions were fundamentally different, with lower PV penetration, higher available inertia, and sufficient spinning reserve. The 2025 events therefore reflect the convergence of higher PV variability and reduced system flexibility, creating a narrow operational margin in which otherwise normal PV fluctuations can lead to severe frequency excursions. This analysis confirms that frequency instability at PT OEC is not caused by solar PV malfunction, but by structural limitations in fast-response balancing capability under constrained operating conditions, providing a clear foundation for subsequent root cause analysis and solution prioritization.

The interaction between solar PV output and grid frequency was analyzed to determine whether PV variability directly drives frequency instability in PT OEC's power system. Under normal operating conditions, correlation and regression analysis between PV output and frequency deviation indicate a very weak linear relationship, with correlation coefficients close to zero and slopes near negligible values. These results show that PV fluctuations introduce only minor short-term frequency "jitter" that remains within acceptable operational limits. Frequency behavior during normal conditions is therefore governed by overall system dynamics, including load variation and gas turbine dispatch, rather than by PV output alone. This confirms that, when sufficient spinning reserve and system inertia are available, the grid is capable of absorbing routine PV variability without significant frequency excursions.

In contrast, high-resolution analysis of the major disturbance events on 22 May and 1 June 2025 reveals a different interaction pattern under constrained operating conditions. One-second data show that sharp frequency declines closely follow cumulative PV output drops, confirming that PV variability acted as an immediate triggering factor. However, the severity of the frequency collapse was determined by system conditions, particularly low spinning reserve and reduced inertia due to generator outages and base loaded gas turbines. On other days with comparable PV ramp rates but adequate reserve, similar PV fluctuations did not result in abnormal frequency deviations. These findings demonstrate that PV variability alone does not cause frequency instability; rather, instability emerges when PV fluctuations coincide with insufficient system flexibility, highlighting the importance of fast-response balancing capability in high-PV-penetration industrial grids.

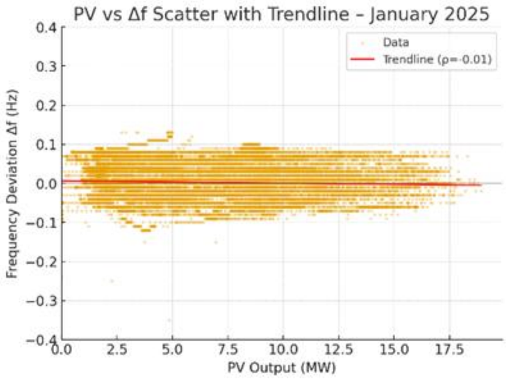

Figure 3. Typical daily scatter plots with trend of PV power vs frequency deviation of each month

Source: PV and frequency data analysis, PT OEC, 2025

Kepner-Tregoe Root Cause Analysis

The major frequency disturbances observed on 22 May and 1 June 2025, which resulted in Under-Frequency Load Shedding (UFLS) activation, represent abnormal operational events with significant reliability and business implications. Given their episodic nature, high severity, and involvement of multiple interacting factors, Kepner–Tregoe (KT) Problem Analysis was applied to establish a structured, fact-based diagnosis of the underlying causes. The analysis integrates operational data, event records, system configuration, and stakeholder insights to distinguish symptoms from causes and to determine whether solar PV variability acted as a root cause or merely a contributing factor. The KT Situation and IS/IS NOT analyses confirm that frequency instability is system-wide, occurs only under specific operating conditions, and did not exist prior to large-scale PV integration, indicating that the issue is structural rather than equipment-related.

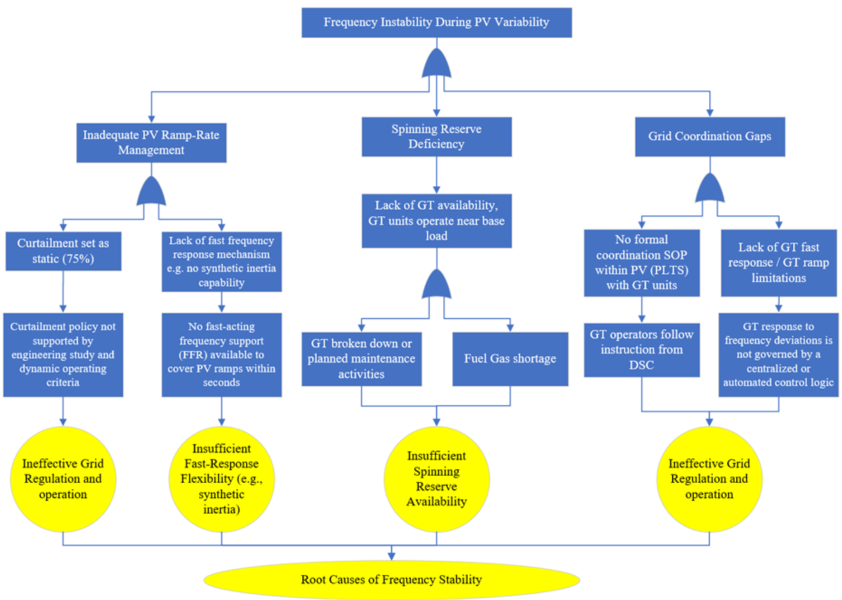

Figure 4. Fault Tree Analysis about Frequency Instability During PV Variability
Source: KT analysis results, 2025

Business Solution

This study evaluates alternative business and operational solutions to address the verified root cause of frequency instability at PT OEC—namely, insufficient effective spinning reserve and limited fast-response balancing capability under high solar PV variability. Building on the results of the Kepner–Tregoe (KT) Root Cause Analysis, a structured decision-support approach combining KT Decision Analysis and the Analytic Hierarchy Process (AHP) is applied to prioritize feasible interventions. The evaluation accounts for PT OEC's operational constraints, including gas turbine availability, fuel limitations, and the requirement for high supply reliability in critical oil and gas operations. Rather than selecting a single solution in isolation, the AHP framework is used to rank and sequence complementary alternatives based on reliability impact, economic considerations, implementation complexity, and strategic flexibility. The resulting prioritization informs a phased implementation strategy, ensuring that immediate operational risks are mitigated while enabling longer-term structural investments that maximize the value and reliability contribution of the solar PV portfolio.

Decision Context and Alternatives

The key decision faced by PT OEC is to determine the most appropriate combination of operational and investment measures to mitigate frequency instability while maximizing the long-term value of its 25 MWp solar PV portfolio.

Based on engineering assessments and stakeholder interviews, four complementary alternatives were identified to address different dimensions of the verified root causes:

1. GT Spinning Reserve Optimization, which focuses on maintaining sufficient reserve headroom during PV operation to mitigate frequency excursions with minimal capital investment.
2. PV–GT Coordination Standard Operating Procedure (SOP), aimed at improving operational consistency and reducing operator-dependent responses during PV ramp events.
3. Battery Energy Storage System (BESS) deployment, providing fast frequency response and synthetic inertia to directly mitigate rapid net-load changes under low-inertia conditions.
4. Dynamic Curtailment Optimization, which limits extreme PV ramp rates under constrained system conditions at the expense of reduced energy yield.

Together, these alternatives address reserve adequacy, operational coordination, fast-response capability, and PV variability management, forming the basis for structured prioritization using the Analytic Hierarchy Process.

KT Decision Analysis – Musts & Wants

Following the verified root causes identified through Kepner–Tregoe (KT) Problem Analysis, KT Decision Analysis is applied to structure the evaluation of solution alternatives by distinguishing non-negotiable requirements (Musts) from comparative decision criteria (Wants). This approach ensures that only technically acceptable and operationally safe alternatives are considered before relative prioritization is performed using the Analytic Hierarchy Process (AHP).

Musts (Non-Negotiable Requirements)

An alternative must satisfy all Must criteria to remain eligible for further evaluation:

1. M1 – Grid Code and Protection Compliance
   The alternative must mitigate frequency instability without violating grid code requirements, protection settings, or UFLS coordination.
2. M2 – Technical Feasibility within the Existing System Context
   The alternative must be implementable within PT OEC's GT-dominated system architecture and existing control infrastructure.
3. M3 – Operational Safety and System Reliability
   The alternative must not introduce additional safety risks or reduce overall system reliability under normal or stressed conditions.

Based on engineering assessment and stakeholder input, all four shortlisted alternatives (GT spinning reserve optimization, PV–GT coordination SOP, BESS, and dynamic curtailment optimization) satisfy these Must requirements and are retained for prioritization.

Wants (Decision Criteria for Prioritization)

Differences among the eligible alternatives are evaluated using the following Wants, which constitute the AHP decision criteria:

4. C1 – Frequency Stability Improvement: Effectiveness in reducing frequency excursions, ROCOF, and UFLS risk.
5. C2 – Impact on PV Energy Yield: Ability to preserve or enhance usable PV energy and realized renewable value.
6. C3 – Investment Cost and Economic Impact: Relative CAPEX, OPEX, and lifecycle cost implications.
7. C4 – Implementation Time and Complexity: Effort, duration, and organizational complexity required for implementation.
8. C5 – Operational Complexity and Maintainability: Impact on operational workload, training needs, and long-term maintainability.

These criteria form the basis of the AHP model used to prioritize and sequence the solution alternatives.

AHP Model Structure

The Analytic Hierarchy Process (AHP) model in this study is used to prioritize and sequence solution alternatives addressing grid frequency instability at PT OEC, rather than to select a single solution in isolation. The model reflects the multi-dimensional nature of the decision problem, in which reliability, economic impact, and implementation feasibility must be considered simultaneously.

The AHP hierarchy is structured into three levels:

Goal: Prioritize solution alternatives that improve frequency stability while maximizing the operational value of the 25 MWp solar PV portfolio.

Criteria:

1. C1 – Frequency Stability Improvement
2. C2 – Impact on PV Energy Value
3. C3 – Investment Cost and Economic Impact
4. C4 – Implementation Time and Complexity
5. C5 – Operational Complexity and Maintainability

Alternatives:

1. A1 – GT Spinning Reserve Optimization
2. A2 – PV–GT Coordination SOP
3. A3 – Battery Energy Storage System (BESS)
4. A4 – Dynamic Curtailment Optimization

This hierarchical structure forms the basis for pairwise comparison, weighting, and sensitivity analysis in the subsequent AHP evaluation.

Pairwise Comparison of Criteria

The relative importance of decision criteria was determined using the Analytic Hierarchy Process (AHP) based on Saaty’s 1–9 scale and expert judgment synthesized from key stakeholders, including the DSC Supervisor, Electrical Engineer, and Electrical Manager. Moderate preference values were intentionally applied to reflect PT OEC's operational realities, where frequency stability is the dominant concern but decisions remain constrained by execution feasibility, operational capability, and cost considerations. Frequency stability improvement (C1) was assessed as more important than investment cost, implementation time, and operational complexity, and slightly more important than PV energy yield, reflecting the critical business risk associated with under-frequency load shedding and production interruption. The resulting normalized weights as shown on table 5

Table 5. Criteria Weights

Criteria	Description	Weight
C1	Frequency Stability Improvement	**0.39**
C2	Impact on PV Energy Yield	**0.23**
C3	Investment Cost	**0.10**
C4	Implementation Time & Complexity	**0.14**
C5	Operational Complexity & Maintainability	**0.14**
	Total	**1.00**

Source: AHP calculation results, 2025

The consistency ratio of the criteria comparison matrix is below 0.1, confirming that the expert judgments are acceptably consistent and suitable for subsequent alternative prioritization.

Pairwise Comparison of Criteria

Following the determination of criteria weights, pairwise comparisons of solution alternatives were conducted under each evaluation criterion using the Analytic Hierarchy Process (AHP). The purpose of this step is not to eliminate any alternative, but to assess their relative contribution to frequency stability improvement, PV energy value preservation, cost efficiency, implementation feasibility, and operational sustainability. In line with the Kepner–Tregoe Decision Analysis perspective, all alternatives are considered complementary and potentially deployable within a phased implementation strategy.

The comparison results indicate clear performance differentiation across criteria. Battery Energy Storage System (BESS) consistently ranks highest for frequency stability improvement and PV energy yield, reflecting its superior fast-response and balancing capability. Operational and procedural solutions—namely GT spinning reserve optimization and PV–GT coordination SOP—perform strongly in cost, implementation speed, and operational simplicity, while dynamic curtailment optimization offers moderate benefits by limiting extreme PV ramps at the expense of energy yield. The aggregation of local priorities across all criteria, weighted by their relative importance, yields the global priority scores summarized in Table 6 (Global AHP Results). This table presents the integrated ranking of alternatives and forms the basis for subsequent interpretation and implementation planning.

Table 6. Global AHP Results

Alternative	C1 (0.39)	C2 (0.23)	C3 (0.10)	C4 (0.14)	C5 (0.14)	Global Priority
A1 - GT Reserve Optimization	0.27	0.11	0.27	0.27	0.23	**0.23**
A2 - PV–GT Coordination SOP	0.09	0.07	0.48	0.48	0.42	**0.22**
A3 - BESS	0.48	0.56	0.08	0.09	0.12	**0.36**
A4 - Dynamic Curtailment Optimization	0.16	0.26	0.17	0.16	0.23	**0.19**

Source: AHP calculation results, 2025

Sensitivity Analysis

Sensitivity analysis was conducted to test the robustness of the AHP-based prioritization and to examine how changes in managerial preferences influence the ranking of solution alternatives. By systematically varying the weight of each decision criterion, the analysis evaluates whether the preferred solution remains stable or shifts under different strategic and operational emphasis. The sensitivity graphs were generated using SuperDecisions software, where changes in criterion weights are mapped against the global priority of each alternative.

The results show that the preferred alternative is highly dependent on the dominant managerial objective. When frequency stability (C1) is increasingly prioritized, Battery Energy Storage System (BESS) rapidly becomes the dominant solution, reflecting its superior fast-response capability and effectiveness in mitigating severe frequency excursions. A clear switching threshold is observed, indicating that once reliability becomes a primary concern, structural solutions such as BESS are favored over procedural or operational measures. Conversely, when investment cost (C3), implementation speed (C4), or operational simplicity (C5) dominate the decision context, low-capital and organizational solutions—particularly PV–GT Coordination SOP and GT spinning reserve optimization—emerge as the preferred options.

In contrast, the sensitivity analysis for PV energy yield (C2) exhibits no switching behavior across the entire weight range. BESS consistently remains the highest-ranked alternative, indicating that PV value maximization is structurally linked to physical system flexibility rather than procedural or curtailment-based measures. This finding confirms that alternatives such as dynamic curtailment or reserve optimization can mitigate risk but cannot substitute for storage in preserving renewable energy value.

From a managerial perspective, the sensitivity analysis confirms that the AHP results are robust and context-sensitive rather than arbitrary. BESS is strongly preferred under reliability- and value-driven decision regimes, while operational and procedural solutions are rational choices under cost-constrained, time-critical, or organizationally conservative conditions. These findings support a phased implementation strategy, where low-cost operational measures serve as immediate risk mitigations, and BESS is positioned as a strategic resilience investment aligned with elevated system risk, higher PV penetration, and long-term sustainability objectives.

Implementation Plan and Roadmap

Based on the validated root cause analysis and the AHP–sensitivity results, this study proposes a phased implementation plan that translates the decision model into actionable managerial steps. The plan is intentionally designed as a sequencing strategy rather than a "single-solution-only" recommendation, acknowledging that the preferred intervention depends on PT OEC's risk appetite, capital availability, and organizational readiness. In general, the sensitivity findings indicate that operational and procedural measures are most attractive when decisions are dominated by cost, implementation speed, and operational simplicity (C3–C5), whereas structural flexibility solutions such as BESS become decisive under reliability- and PV value-driven regimes (C1–C2).

Accordingly, the roadmap is structured into three phases. The short-term phase focuses on immediate operational risk mitigation through low-CAPEX actions, primarily PV–GT coordination SOP and GT spinning reserve optimization, to reduce exposure to severe frequency excursions during PV ramp events. The medium-term phase strengthens system readiness by improving PV forecasting integration, conducting detailed grid and dynamic studies, and developing governance and capability building to reduce execution and maintainability risks before major investments. The long-term phase delivers structural resilience and value creation through a phased BESS deployment integrated with operational systems, enabling fast frequency support, reduced curtailment, and a more future-proof renewable integration pathway.

Table 4.3 summarizes the proposed implementation plan and roadmap, highlighting each phase's time horizon, primary focus, key actions, and its analytical justification based on the AHP and sensitivity outcomes. The table provides a clear "closing loop" between the decision analysis results and the recommended sequencing logic for implementation at PT OEC.

Table 7. Implementation Roadmap

Phase	Time Horizon	Primary Focus	Key Actions	Analytical Justification
Phase 1: Short-Term	0–12 months	**Operational Risk Mitigation**	- PV–GT coordination SOP implementation - Optimization of GT spinning reserve policies - Enhanced operational monitoring during PV ramp events	Preferred under **C3 (Cost)**, **C4 (Implementation Time)**, and **C5 (Operational Complexity)** sensitivity scenarios. Rapid, low-CAPEX actions to reduce immediate frequency risk.
Phase 2: Medium-Term	1–3 years	**System Strengthening & Readiness**	- Improved PV forecasting and dispatch integration - Detailed system and dynamic stability studies - Governance framework and decision thresholds - Capability	Addresses transition zone, reduces execution and maintainability risks prior to structural investments.

Phase	Time Horizon	Primary Focus	Key Actions	Analytical Justification
			building and pilot initiatives	
Phase 3: Long-Term	3–5 years	**Structural Resilience & Value Creation**	- Phased deployment of BESS - Integration with EMS and operational systems - Scalability aligned with PV growth	Dominant under **C1 (Frequency Stability)** and **C2 (PV Energy Yield)** sensitivity. Resolves structural root cause and enables sustainable PV integration.

Source: Researcher's analysis and recommendations, 2025

CONCLUSION

This study examined the operational and business impacts of integrating a 25 MWp solar PV portfolio into PT OEC's internal power system, emphasizing PV value realization and grid frequency stability through an integrated framework combining PV performance analysis, frequency assessment, Kepner–Tregoe (KT) root cause analysis, Analytic Hierarchy Process (AHP), and sensitivity analysis. Results revealed that PT OEC's PV portfolio achieved specific yields of 3.1–3.9 kWh/kWp/day and performance ratios of 0.70–0.78—within normal tropical ranges but at the lower benchmark boundary—due to operational constraints like conservative curtailment rather than technical failure. Frequency analysis showed PV variability posed no issue under normal conditions but triggered severe excursions and UFLS activation during constrained scenarios with insufficient spinning reserve and inertia; KT identified inadequate fast-response balancing as the primary root cause, amplified by PV fluctuations. AHP prioritized Battery Energy Storage Systems (BESS) for reliability-focused decisions, with sensitivity analysis favoring operational measures under cost- or speed-driven scenarios, supporting a phased, complementary strategy. Overall, PT OEC's challenges proved systemic, underscoring the need for enhanced system flexibility via structured decisions. For future research, exploring hybrid BESS-hybrid renewable configurations or AI-driven predictive balancing in similar industrial grids could validate scalability across diverse tropical settings.

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